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VELOCITY OF DETONATION FROM STREAK CAMERA RECORDS

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VELOCITY OF DETONATION FROM STREAK CAMERA RECORDS

By

John O. Erkman

ABSTRACT: Some of the problems associated with measuring the detonation velocities of cylindrical charges are discussed. The streak camera is used as the recording instrument so that data reduction requires differentiation of numerical data. The emphasis is on methods of determining if the records represent steady or nonsteady events.

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VELOCITY OF DETONATION FROM STREAK CAMERA RECORDS

This work was carried out under ORDTASK 033 102 F009 06 01 which is a systematic investigation of the explosive behavior of composite propellant models. The report will interest those who have to measure and correct detonation velocities of exploding charges by use of streak cameras.

E. F. SCHREITER
Captain, USN
Commander

ALBERT LIGHTBODY
By direction

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INTRODUCTION

I. The need for accurate values of the detonation velocity in the study of organic high explosives is discussed by Price.[1] The detonation velocity is an important parameter in the study of inorganic materials such as ammonium perchlorate for the same reasons. Methods for measuring the velocity of detonation are reviewed by Campbell et al[2] with special emphasis on chronographic methods. In a continuing program at the Naval Ordnance Laboratory, the detonation velocities of both organic and inorganic materials is determined by the use of a streak camera. This report is primarily concerned with the problem of extracting as much information as possible from the streak camera record.

The principal material being studied in the present project is ammonium perchlorate (AP) loaded in cylindrical charges at densities ranging from 0.5 to 1.55 g/cc. Mixtures with AP are also studied, the second component being wax, aluminum powder, or an organic high explosive. Other materials included in the program are nitroguanidine and dinitrotoluene. The study of such a variety of materials at varying densities presents many challenging problems in the preparation of charges and in the use of the streak camera, however, preparation of the charges and the handling of the streak camera will not be discussed.

The most challenging aspect of the reduction of the data from the streak camera in the program is that of determining if the detonation was steady. It is relatively simple to extract a velocity from the data. Steadiness must be determined from the acceleration of the event. This requires, in effect, that the numerical data be differentiated twice. Various methods are discussed which are being used in classifying the records as those of steady or nonsteady processes.

Also discussed in this report are the effects of overboostering the acceptor charge and the effect of the geometry of the charge on the results. The latter comes about because the streak camera records

the progress of the detonation along the exterior of the cylindrical charges. Limitations of the firing facility restrict the length to diameter ratio (L/d) to about 3.5 for 3.0 inch diameter charges. For such charges, the velocities obtained by observing the periphery of the charges must be corrected to give the actual velocity which would be observed if the axis of the charge could be viewed.

II. CURVATURE OF A STREAK CAMERA RECORD. As noted above, the nature of the research which prompted this discussion requires the accurate determination of the velocities of steady detonations in cylindrical charges of propellants. Unfortunately, there is no a priori knowledge concerning the steadiness of the reaction. This knowledge must come from an examination of the streak camera record which can be done by comparing the trace with a straight edge. But how much can the trace deviate from the straight edge? As a start in answering the question, it is helpful to calculate the radius of curvature of a typical trace. The radius of curvature, R, is given by

$$R = \frac{[1 + (x')^2]^{3/2}}{x''} \qquad (1)$$

where x' and x" are the first and second derivatives of a function of time, t, which is fitted to the record. For simplicity, assume that the trace can be described by

$$x = a + bt + ct^2,$$

so that the derivatives are easily calculated. The situation is diagrammed in Fig. 1 where the trace is represented by the curve. The straight line (a chord) passes through the beginning and end of the trace. If velocity is v_0 at (0,0) and v_1 at (t_1, x_1), then

$$\frac{v_0 - v_1}{v_0} = P = \frac{b - (b + 2ct_1)}{b} = \frac{-2ct_1}{b}$$

or

$$c = -bP / 2t_1, \qquad (3)$$

so that c can be evaluated for typical values of t_1 and b for appropriate values of P. Note that b is the velocity at (0,0) in Fig. 1. Now the equation for the radius of curvature becomes,

$$R = \frac{-t_1}{bP} \left\{ 1 + b^2 \, (1 - P/2)^2 \right\}^{3/2}, \tag{4}$$

where the first derivative was evaluated at $t_1/2$. When the change in velocity is zero ($P = 0$), the radius of curvature is infinite. Curves showing the relation between R and P (in percent) are given in Fig. 2. For two cases, the trace is assumed to be inclined at an angle of 45° to the time axis. For one of these traces, t_1 is represented by a length of 5.0 cm, for the other, t_1 is 2.5 cm. The third curve is for $\theta = 60^\circ$, and $t_1 = 2.9$ cm. These values are fairly typical, that is, the trace for many experiments is inclined at 45° and is 5.0 cm long in the time direction. Note that t_1 is given in units of length so that the results can be applied directly to the film record. In these units, the value of b is simply $\tan \theta$ with no conversion factor. The value of R for $P = -2\%$ ranges from 348 to 696 cm.

Values of R are not as helpful as are values of h, see Fig. 1. The distance from the circle to the straight line is

$$h = R - 0.5 \sqrt{4R^2 - L^2} \tag{5}$$

where L is the length of the chord of the trace. Figure 3 shows how h varies with P for the three cases described above. For $P = 2\%$, the values of h is about -0.011 cm for $\theta = 45^\circ$, $t_1 = 5$ cm. This means that in order to detect a 2% decrease in velocity, one must detect a separation of 0.01 cm between the straight edge and the trace. For ideal traces this may be possible. But where the edge of the trace is fuzzy or blurred, the situation is difficult. Magnification increases the separation but may be of no real help for indistinct records. The situation is worse for the "half record", i.e., for $t_1 = 2.5$cm, and $\theta = 45^\circ$. A separation of 0.004 cm must be detected for $P = 2\%$.

Curves such as those discussed above help in the classification of records as representing constant or varying velocity. After a preliminary screening by direct observations, those records which seem to represent steady phenomena are investigated further. One step in the analysis is a determination of the constants for the best quadratic

fit. Once the constants b and c are evaluated, the change in velocity, P can be calculated for the record. The result may be useful in confirming the original classification of the record.

III. QUALITY OF THE STREAK CAMERA RECORD. If all records were near perfect, data reduction would present fewer problems. Most records have some defects, due primarily to the quality of the charge. For example, if the surface of the charge is pitted, or if one component in the mix tends to clump, the record will not be smooth. Also, if the charge is assembled from a set of pellets, the record may not be smooth because each pellet detonates at a slightly different velocity. The difference in velocity could be caused by variation of density from pellet to pellet. Hence data reduction techniques must be sufficiently versatile to handle records of different quality.

Data reduction follows the common route of digitalizing the record and performing numerical operations. The records are read on a projecting machine having two cross wires. The inter-section of the wires is placed on the trace, and a card is punched. Because of non-uniformities in many of the records, the data are not read at equal intervals in t. This is somewhat unfortunate, because many techniques for data reduction are simpler for data spaced equally in one of the variables. Fortunately, more generalized treatments can be obtained at low cost with modern computing equipment.

One way to examine the digital data for quality is to take the ratio of the change of x to the change of t between each succeeding pair of points. This is a crude form of differentiation and is certainly permissible when it is recalled that the record is nearly straight. The occasional wide variation of $\Delta x/\Delta t$ indicates that an error has been made in reading a point, or that the record is rough. It is possible to set some criteria on which bad points can be discarded. This has not yet been developed for the current program.

After the data are on punched cards, a computer is used to determine the best straight line which fits the data. This provides another means of studying the scatter of individual points. If one, or a few points lie off the line by an inordinate amount, the points should be either discarded, or given a lower weight in subsequent data reduction.

The slope of the straight line which fits the data is proportional to the velocity of the phenomenon being studied. The computer program provides an estimate of the standard deviation of the coefficients of the function used in the fit. Hence the standard deviation of the velocity is available. Values of the standard deviation in the velocity are being studied for correlation with the occurrence of bad points, fuzzy traces, etc.

IV. CORRECTION FOR CHARGE GEOMETRY AND BOOSTER. The streak camera records the progress of the detonation along the exterior of the charge. When the charge length to diameter ratio is 5 or less, the velocity derived from the record must be corrected to give the velocity along the axis of the charge. This correction has been discussed previously by Clairmont and Jaffe[3]. The situation is represented by the diagram in Fig. 4, which shows the cross-section of a charge. Point initiation is assumed to have occurred at point A, following which the detonation front remains spherical. At a later time the front is represented by the arc of the circle, BCD. Using the point A as the origin, the distance along the axis of the charge to the instanteous location of the front is y. Similarly, using E as an origin, the distance along the edge of the charge to the front is represented by z. Note that AE is the radius of the charge, d/2, and that $\overline{AC} = \overline{AD}$ and

$$y^2 = (\overline{AE})^2 + (\overline{DE})^2 = (d/2)^2 + z^2 \tag{6}$$

Differentiating and substituting for y gives

$$y' = z' / \sqrt{1.0 + 0.25\ d^2/y^2} \tag{7}$$

where z' is the velocity determined from the streak camera record. Let D = y', the velocity along the axis of the charge and V = z', the observed velocity. There results

$$D = V/\sqrt{1 + 0.25\ (d/L)^2} \tag{8}$$

where L is the length of the charge up to the point observed.

The assumption concerning the curvature of the detonation front has been discussed previously[3] and appears to be justified for charges of tetryl. It has not been checked for the propellants now being investigated.

Values of the correction factor, $F = (1.0 + 0.25\ (d/L)^2)^{-1/2}$ are given in Table I. In practice the combined length of the acceptor and donor charges is 10 inches. For a 3 inch diameter charge, $L/d = 3.3$ and $F = 0.989$ so the correction amounts to about 1%.

TABLE I

Correction Factor F as a Function of L/d

L/d	F
1	0.8940
2	0.9700
3	0.9864
4	0.9923
6	0.9965
8	0.9980
10	0.99875
11	0.99896

The situation is somewhat worse than this because the velocity V is determined at some distance from the end of the charge.

The effect just described introduces some uncertainty in classifying records. For example, when L/d is 4 or less, the effect described above should result in a detectable curvature of the records. This curvature must be evaluated and compared with the expected curvature for a final classification of the record. The appropriate question concerns the change in the velocity V over the observed distance, usually 2.5 inches. At the beginning of the record, the detonation has reached the point $z = z_1 = \overline{DE}$ (see Fig. 4) so that the observed velocity is $V_1 = F_1D$. At the end of the record, $z = z_2$ and $V_2 = F_2D$, it being assumed that the velocity D is a constant. Hence the change in velocity is $D(F_1 - F_2)$ and the % change with respect to the velocity V_1 is

$$G = 100\ (F_1 - F_2)\Big/F_1, \qquad (9)$$

due to the geometry of the charge.

The following example illustrates the use of the above results. A 3 inch diameter charge gave a velocity of 4.64 mm/μsec at a

distance of 6.7 cm from its free end. The total length of the charge was 10 inches or 25 cm. So at 6.7 cm from the end, L/d is about 2.4 and $F_1 = 0.978$. At the end of the charge where L/d = 3.3, $F_2 = 0.9885$ and G = -1.1, which means that the velocity decreases about 1% due to the effect of geometry. Analysis of the record showed that the velocity V decreased about 2% during the observation. Thus the observed decrease is greater than the expected decrease so that the detonation could, in principle, be failing.

The correction described above can be expedited somewhat by use of the curves shown in Fig. 5. The curves are for 25 cm long charges for which the last X cm are observed by the streak camera. The abscissa in the Fig. 5 is X and the ordinate is -G, the % change in velocity expected from the geometry effect.

Most of the model propellant mixtures being investigated have been boostered by a charge of high explosive such as tetryl or pentolite. The detonation velocity of the booster is greater than that of the acceptor and than that given above. The derivation of the correction is based on the assumptions that the detonation front is spherical not only while it is in the booster but also after it is entirely in the acceptor charge and that the detonation velocity in the acceptor is constant. It is recognized that these assumptions over-simplify the situation. The situation is diagrammed in Fig. 6 which shows the booster as having the same diameter as the test charge. The length of the booster, $\overline{DE}$ is represented by h, the radius of the charges by r and the detonation front by the arc BCD. Assume that the center of the circle is at the point 0,k), and that its radius is R. Substituting the coordinates of points C and D into the equation of a circle gives

$$(H - k)^2 = R^2 \tag{10}$$

and

$$r^2 + (h - k)^2 = R^2, \tag{11}$$

where H is the distance $\overline{AC}$. Solving for k gives

$$k = \frac{H^2 - h^2 - r^2}{2(H - h)} \tag{12}$$

so that the apparent origin of the spherical front is determined.

The quantity H is eliminated by noting that the same intervals of time are required for the detonation to reach points C and D. Let D_a and D_b be the detonation velocities in the acceptor and booster charges respectively. The results are

$$\frac{\sqrt{h^2 + r^2}}{D_b} = \frac{h}{D_b} + \frac{(H - h)}{D_a}, \tag{13}$$

from which

$$H = h(1 - N) + N\sqrt{h^2 + r^2} \tag{14}$$

where

$$N = D_a/D_b.$$

Combining equations 12 and 14 gives

$$k = (1-N)\left[1 - \frac{r^2\ (1 + N)}{2N\sqrt{h^2 + r^2} - h}\right] \tag{15}$$

Note that k vanishes when N = 1, i.e., when the booster has the same detonation velocity as the acceptor. When N <1, k is negative and the effective booster length is (h - k).

The dependency of k on N for 1.0, 2.0 and 3.0 inch diameter charges when boostered by either 1.0 inch or 2.0 inch long booster pellets is shown in Table 2 and Fig. 7. The value for k varies more with charge diameter when the booster length is 1.0 inch. than when the length is 2.0 inches. For N = 0.5, the effective length, (h - k), of a 2.0 inch long booster is about 4.2 inches. Such a booster is normally used with an 8.0 inch long acceptor charge, so that the effective charge length is about 12.2 inches. When 9.0 inch long charges are used with 1.0 inch long boosters, the effective lengths are 11.1 inches for 1.0 inch diameter and 11.6 inches for 3.0 inch diameter charges.

When N <1, the effective charge length, L_e, is greater than the actual charge length, see Table 3. Thus the use of the actual charge length (donor plus acceptor) in Eq. 15 results in values of F which are too small. Use of the effective charge length gives larger values

of F and results in a more nearly correct value of the axial velocity. The following example may be useful in demonstrating these corrections. Assume the charge is 3.0 inches in diameter, and that the donor is 1.0 inch long. Thus for N = 1, the

TABLE 2

k in inches for 1.0 and 2.0 inch long boosters

	1.0 inch long booster			2.0 inch long booster		
CHARGE DIAMETER, INCH } →	1.0	2.0	3.0	1.0	2.0	3.0
N	k	k	k	k	k	k
0.2	-4.28	-4.99	-5.93	-8.15	-8.57	-9.20
0.4	-1.62	-1.93	-2.34	-3.06	-3.25	-3.52
0.6	-0.73	-0.89	-1.09	-1.37	-1.46	-1.60
0.8	-0.27	-0.34	-0.43	-0.51	-0.55	-0.61
1.0	0.00	0.00	0.00	0.00	0.00	0.00
1.2	0.19	0.24	0.31	0.34	0.38	0.425
1.4	0.33	0.43	0.56	0.59	0.65	0.74

effective length, L_e, is the same as the actual combined length of the charges, and F = 0.9887. For smaller values of N, L_e is increased, and F is increased, that is, the observed velocity is more nearly equal to the axial velocity,

TABLE 3

Correction to Observed Velocity

N	k	L_e inches	L_e/d	F
1.0	0	10	3.33	0.9887
0.8	-0.4	10.4	3.47	0.9896
0.6	-1.1	11.1	3.70	0.9909
0.4	-2.3	12.3	4.10	0.9926
0.2	-5.9	15.9	5.30	0.9956

The observed velocity is about 1% too great for a 9.0 inch long, 3.0 inch diameter charge of ammonium perchlorate having a detonation velocity of about 4 mm/μsec when boostered by tetryl having a

detonation velocity of 7.2 mm/μsec.

V. DIFFERENTIATING THE STREAK CAMERA RECORD. After a record passes a visual screening for lack of curvature it must be differentiated. This usually requires that the record be reduced to digital data. If a graphical method is used the data are plotted and a curve is drawn through the points. Next, normals or tangents are constructed at intervals along the curve and their slopes are determined. Thus the derivative is determined at as many points along the curve as desired.

Graphical differentation has been discarded because it is a time consuming process and the results are often unsatisfactory. There is a degree of subjectivity in drawing a continuous curve through the plotted points which makes reproducibility difficult. Constructing the tangents (or normals) is also subjective and is a source of error. However, graphical methods may be useful especially during the early part of an investigation when the behavior of the derivative is unknown. If the curve drawing is done both carefully and honestly, abrupt changes may be detected in the slope of the curve. These abrupt changes may be of considerable interest, as in the case of attenuation experiments[4].

Graphical methods depend on the accurate measurement of angles. One of the difficulties with measuring angles is illustrated by the following. Assume the angle θ is measured, Fig. 8. The velocity is proportional to k tan θ, when k is a constant of proportionality which is assumed to be well known. The relative error in % is

$$R = 100\,\frac{dv}{v} = \frac{100\ \theta}{\sin\theta\ \cos\theta} = \frac{200\ d\theta}{\sin(2\theta)} \tag{16}$$

which has a minimum at $\theta = 45^\circ$ where it is twice the error in θ. Thus the best determinations of velocity are possible when $\theta = 45^\circ$. The behavior of $R/d\theta$ is shown in Fig. 9. Records for which $30^\circ < \theta < 60^\circ$ are probably suitable for data reduction by measuring the angle. The problem is discussed in more detail by A. S. Bubovik[4].

The availability of electronic digital computers has increased the use of polynomials and other functions for fitting data. Polynomials are easily differentiated and a table of the values of the

derivative is provided by the computer. If the scale factors are also included in the input to the computer, the velocity is given as a function of one of the variables, x or t, in the output. Some comments should be made concerning this procedure.

For one thing, the phenomena being studied may not obey a polynomial representation. In the simple problem being discussed here, the velocity is expected to approach a constant value for reasonable values of L/d. A polynomial does not extrapolate to give a derivative which approaches an asymptate. Hence the choice of a polynomial may be poor when the physics of the situation is considered.

Polynomials can be made to fit the data very well simply by using higher order terms. When the degree is 3 or greater, one or more inflection points are possible. These almost invariably spoil any extrapolation, and they may introduce changes in the derivatives which are not expected from the physics of the situation. Great care should be used in the interpretation of polynomial fits to data, especially when one polynomial is fitted to the entire set of data. A piecewise fit may sometimes give more useful results. Over small ranges of the data, even first and second degree polynomials may be useful. For the present study, first and second degree polynomials are useful in determining the velocity because (1) the data are nearly linear and (2) comparison of the fits with the data give some indications as to both the linearity of the data, Sec. II, and the scatter in the data, Sec. III.

Some curvature in the data is expected because of the geometrical effect discussed in Sec. IV. This should be more evident in the charges for which L/d is small (4 rather than 10). It would be well if this curvature could be detected by the numerical analysis of the data. In order to do this, one may use functions such as the quadratic mentioned above. Another function which could be used is

$$x = At + C(1 - e^{-Bt}). \tag{17}$$

As t becomes large, the first derivative approaches a constant value, A. This is a desirable feature for the present application - at least for charges which have steady axial velocities. The function has been

used in this application previously[6] but is not used in the present data reduction operations. It could possibly be used in place of the quadratic for determining the radius of curvature of a trace, see Sec. II.

It was noted above that the approach of the first derivative of Eq. (17) to a constant value was desirable. Other functions have this same desirable behavior. Some can be found in the analysis of one dimensional shock waves, two of which are discussed in the following. Only one of them has been used in the present program of data reduction.

The decay of a shock wave due to a following rarefaction wave is discussed by Lax[7]. The path of the shock wave is given by

$$At(x-t)+Bt+Cx = 0 \qquad (18)$$

where

$$A = -\left(\frac{41}{5}\right) - u_1 - c_1$$

$$B = -\left(\frac{41}{5}\right) k \ (u_1 + c_1 - 1)$$

$$C = -k \ (u_1 + c_1 - 1).$$

In the above relations, u_1 and c_1 are the shock induced particle velocity and the shocked induced sound speed, respectively, and k is an equation of state parameter. The interesting feature of this representation is the cross product of the variables. Means are available for fitting the constants to the data in the least square sense. The function actually being used is

$$x = -(A + Bt + Ct^2) \ / \ (D + t). \qquad (19)$$

Its derivatives are

$$dx/dt = -C + (A + CD^2 - DB) \ /(D + t)^2 \qquad (20)$$

and

$$d^2x/dt^2 = 2(DB - CD^2 - A) \ / \ (D + t)^3 \qquad (21)$$

One objectionable feature of Eq. 19 is the singularity in the function, and in its derivatives. There is no inflection point, but there is a change of sign in the second derivative at the singularity. This

shows up in some applications of the function, i.e., the parameter D is negative and its absolute value is in the range of the values of the independent variable t. In the neighborhood of the singularity the calculated values of the velocity and acceleration do not lie on a smooth curve.

It is obvious that the acceleration (Eq. 21) vanishes as t becomes large. The velocity then approaches the constant, -C. Thus the function behaves in the same manner as the exponential function discussed previously. It is this behavior which makes the function of interest in the present context. Because it has four parameters, it should fit the data somewhat differently than Eq. 17.

Another derivation of the path of a decaying shock is given by Fowles[8]. His results are given by the expression

$$C_oB\ (T-T_1)^{3/2} + AC_o\ (T-T_1) - B(X - X_1)\ (T - T_1)^{1/2} + (X - X_1) = 0, \quad (22)$$

where

$$A = -(2\gamma + 3)$$

$$B = [\sigma_o - 2(\gamma + 1)] \Big/ \left[\sigma_o \sqrt{T_3 - T_1}\right]$$

and C_o, T_1, γ, σ, T_3 are constants. This representation has a cross product in common with the Lax expression. It has not yet been applied in data reduction.

The work involved in using such functions as the hyperbolic and the exponential described above is greatly expedited by the use of a subroutine "A General Weighted Least - Square-Fit Subroutine".[9] A useful feature of the subroutine is the calculation of the quadratic mean error (QME) for the overall fit and for each of the parameters involved. The subroutine can be used in different ways to determine the value of the parameters of equations such as Eq. 18. If the equation is fitted as it is written, the values of the QME for some of the parameters may be enormous. This is caused by the singularity which gives large numbers for the matrix which must be inverted in the subroutine. The trouble is circumvented by regarding both x and t as independent variables, and the cross-product term, xt, as the dependent variable.* This approach produces more reasonable values for both the

*This method was suggested by J. W. Forbes.

parameters and for their QME's. The QME of the fit is still calculated on the basis that t is the independent variable and that x is the dependent variable.

Another method for handling the data uses a spline function. This consists of a set of cubic functions which are fitted to the data in a least squares sense. Each cubic represents a subset of the data, and the first and second derivatives are required to be continuous at the joints between adjacent cubics. The set of data may be divided into subsets of 3 or more points. When only a few points are used in a subset, the spline function employs many parameters so that local variations in the data may be followed. This ability to fit the data closely is a characteristic which the spline shares with higher degree polynomials. The spline function smooths the data in about the same sense as the usual smoothing formulas frequently used for data which are equally spaced in one variable. Stated another way, the spline function permits the smoothing of data in those situations where it is thought inadvisable or impossible to advance one variable in equal steps. The spline function parameters are determined by a computer program which also evaluates the derivative. Thus the program accomplishes the same result as the more usual smoothing and differentiation operations on equally spaced data.

VI. RESULTS OF NUMERICAL DATA REDUCTION. Some of the operations which may be performed on the data were described in the previous sections. These operations are performed by a digital computer and the results are displayed in tabular form and in graphical form. The table and the plots will be presented and described in this section. The meaning of the results will be discussed in the following section.

The first line of the computer output, Table 4, gives the shot number to identify the data. The second line gives conversion factors so that measurements from the Telereader can be converted to physical units. The raw data are given in columns 3 and 4 of the columnar part of the table. The converted data are given in column 1 and 2, the units being μsec for time and mm for distance.

The crude values for the instanteous velocities are given in the column headed DXDT. Values in this column should vary very little if the streak camera record is straight and easy to read. Hence any value of DXDT differing significantly from the average signals a bad data point.

The instanteous velocity is given in columns 5 and 7 also. The column labeled SPLINE gives the velocity as evaluated from the spline function, (SF). The column labeled HYPERBOLIC gives the velocity as calculated from the hyperbolic function (HF) Eq. 19. The acceleration as given by the HF is given in column 8. Residuals for the three functions are given in the last 3 columns of the table.

Coefficients for the linear, quadratic and HF are given near the top of the table (XT FIT means the hyperbolic function). Immediately below the value of each coefficient is its percentage error based on the quadratic mean error (QME) of that parameter which is essentially the standard deviation.[10] Where the error in a parameter is large--100% or more--the term involving that parameter should probably be discarded and a new fit should be obtained.

Below the columnar part of Table 4 are results which help to determine if the record represents a steady detonation. The parameters of the quadratic are used to give the acceleration and the time and distance required for a 10% change in the velocity. On the next line is the percent change in the velocity over the time of observation, i.e., the interval of time between the first and last entries in column 1.

The root mean square of the error in the spline function, (SF), is given in the third line from the bottom of the table. The derivative of the SF can be obtained by the use of a subroutine for any value of the time. For example, the subroutine was used to obtain the derivative (the velocity) at each value of the time in column 1 of the table. These values are recorded in column 5. Another set of values are obtained at 45 equally spaced values of the time within the range of the entries of column 1. These results are divided into three groups of 15 each and the average is calculated for each group as well

as for the set of 45 values. These averages are reported on the second line from the bottom of the table. The difference, in percent, of the velocity over each one-third with respect to the overall average is given on the last line.

As an aid in examining the results, plots are prepared showing DXDT and the velocity as computed from the spline function, see Fig. 10. In the plots, values of DXDT are represented by points, while the results of the SF are given as connected points.

VII. DISCUSSION OF RESULTS. The results presented in Table 4 and Fig. 10 for Shot 487 will be discussed first. Later, the results for other shots will be presented and discussed.

Shot 487 gave a good record as is evident from examining the values of DXDT in Table 4 and in Fig. 10. Note that in the table the first value of DXDT is arbitrarily set to zero. This results in a problem with the plotting procedures which is circumvented by making DXDT (1) = DXDT (2) for the plot. The values of DXDT do vary, having a minimum value of 2.65 and a maximum of 3.02. The velocity reported for this shot was 2.86 mm/μsec, the value of B for the linear function. Hence the maximum variation of DXDT with respect to the reported velocity is +5% and -7%. Most of the values lie within ±5%, see Fig. 10. These variations are tolerable and it is probably not necessary to discard the few points which deviate more than 5%.

For the results given here, the data were divided into subsets of four points each in obtaining the fit by the SF. Used in this way, the SF smooths the data considerably so that the velocities from the SF vary less than do the values of DXDT. The SF preserves the general trend of the velocity, however. If greater smoothing had been desired, the number of data points in each subset would have been increased. Note that the values from the spline function (SF) are low at the beginning of the record, as are the values of DXDT. This is frequently observed in the data and the cause is not known. The implication is that the detonation is accelerating. This is not expected, especially in view of the results presented in Sec. IV, which predicts a decreasing velocity. Also note that the velocity drops

near the end of the record so that the average over the last 1/3 is lower than the average over the 1st and 2nd thirds. This latter portion of the data indicates that the detonation is decelerating.

The increase of velocity at the beginning of the record, and its decrease over the latter portion of the record, as shown by the SF, make the data difficult to fit. Note that the residuals for the linear, quadratic and HF fits have a cluster of negative signs near the end of the record and that the last three residuals are positive for all three functions. The maximum residual is about 0.4% of the value of the distance. These small values may be meaningless so that one can, for example, regard the linear fit to be adequate. Hence the velocity of the detonation is 2.86 ± 0.1% (see the value of B for the linear fit). However, the last 5 values of the velocity from the SF are less than 2.86 so it is not clear if the charge detonated at constant velocity.

The quadratic gives a velocity of 2.86 mm/μsec at 11 μsec (the middle of the record) in agreement with the value from the linear fit. Because the value of C is negative, the quadratic also shows that the detonation velocity is decreasing, in agreement with the SF. But observe the errors for B and C for the quadratic, 0.5% and 79% respectively. The latter is so large that little confidence can be placed in the prediction of the acceleration by the quadratic. Hence these computations have been of little help in determining if the detonation was steady.

The data and results for Shot 502 are given in Table 5 and Fig. 11. The charge was 5.08 cm in diameter and about 25 cm long so that the observed velocity should be decreasing slightly (see Sec. IV). This shot is of interest because the quadratic indicates the detonation is accelerating 2.3% over the time of observation. The error in the coefficient C for the quadratic is 25% here compared to 79% for Shot 487 which was discussed previously. Hence the quadratic fits the data of Shot 502 better than that of Shot 487, and the calculated acceleration is more reliable.

A better fit to the data of Shot 502 could possibly be obtained by discarding the data on the lines where the values of DXDT are about 3.47 and 3.52.

The velocities for t = 10 μsec are: (1) linear, 3.304, (2) quadratic, 3.305, (3) HF, 3.290, (4) SF, 3.365. The agreement among the values is good, and is improved if the average over the 2nd third of the record is used for the SF, i.e., 3.307. Note that the results obtained by averaging the results from the SF show acceleration. The "ripple" which is in evidence in Fig. 10 is an interesting feature of this record.

Data and results for Shot 504 are given in Table 6 and Fig. 12. The charge was 2.54 cm in diameter and 25 cm long so that the observed velocity should be close to the axial velocity. The record was difficult to read--see the variations in the values of DXDT. The velocities are: (1) linear, 5.872 ± 0.2%, (2) quadratic, 5.873 ± 0.7%, (3) SF, 6.027, (4) HF, 5.843 where the last 3 values are taken at t = 5.25 μsec. Agreement is remarkable, except for the value from the SF. Averaging over the middle third of the record gives 5.999, which is still larger than any of the other results.

The error in the acceleration, i.e., ± C for the quadratic fit, is so large that the quadratic is useless for the prediction of steadiness. Eliminating a few points at the start and at the end of the record might permit a better determination of the acceleration. Removal of these data would eliminate the large values of DXDT at each end of the plot, Fig. 12.

Each of the three records discussed contains a certain amount of "ripple". This shows up both in the plot of DXDT and in the plot from the SF. This ripple could be the result of faulty bearings in the streak camera. Or the film reader could be defective. It is possible, of course, that the detonations are really not steady. The idea that detonations are unsteady is somewhat abhorrent so that the other possibilities are being investigated first.

In order to check the film reader, objects with straight edges were placed in the projector. In all cases, some ripple was observed

on the plot of the velocity - which was simply the slope of the line as seen on the screen of the machine. Plots from two of these experiments are shown in Fig. 13. The top plot is the result obtained with a stretched thread in the projector. There is a ripple in both the results from the SF and DXDT. Similarly, a ripple is observed for a ruler, see the lower plot in Fig. 13. These results show that either the film reader is defective, or that it is not being used properly. The trouble is thought to be caused by the illuminating system in the machine which consists of several small fluorescent lamps. There is no diffuser or condensing lenses between the lamp and the film. The screen illumination is nonuniform to such a degree that the operator may find it impossible to set the cross wires on the image properly. The machine will be replaced in the near future, and improved results may then be obtained.

In some cases the errors in the coefficients of the hyperbolic function are large. However, the residuals may be as small as those for the linear and quadratic functions. The meaning of the large uncertainties is that the terms involving A and D could be dropped. The result would then be $x + B + Ct = 0$. That is, a linear function is more appropriate for the data. It is of interest to examine the behavior of the hyperbolic function when non-linear data are used. Results were reported[3] for 5.08 cm diameter tetryl charges in work concerned with the correction for the finite length of charges. Data for three of the experiments have been treated in the same way as the propellant data (see Tables 7, 8, and 9). Because the original data, where the units were counts, were not available, the previously converted data were used as input. Hence the 3rd and 4th column are the same as the 1st and 2nd column respectively and distance is in cm rather than mm. There is at least one bad pair of values of x and t in Table 7 (see the value 1.086 in the DXDT column). This bad data set is not smoothed very well by the SF. Curvature is so great that the linear function is useless. The HF fits the data fairly well (see the residuals for the three tetryl charges, Tables 7, 8, and 9 and the values for the QME in Table 10.) The coefficients and their errors are collected in Table 10, as well as results for the three propellant

shots discussed previously. Smaller errors are observed in A and D for the tetryl charges than for the propellant charges. That is, these coefficients are more meaningful for the tetryl data, due to the greater curvature of the (x, t) curve being fitted.

The average velocity from 6 tetryl charges was reported to be 7.17 mm/μsec.[3] The purpose of the referenced work was to demonstrate that the steady detonation velocity could be determined by observing the detonation of relatively short charges. Interpretation of the experimental data required the use of the function

$$x^2 = D^2 t^2 + A D t \qquad (23)$$

in which D and A are parameters. When extrapolated to large values of x and t, this function gives the steady velocity D. The same determination can be made with the HF being discussed here. The velocity in question is simply the value of -C for the HF. For tetryl shots 1, 2 and 3 the velocities are 7.49, 8.52 and 7.72 mm/μsec respectively. These values are all greater than those reported previously, so that Eq. 23 gives better results than the HF. This is not particularly disappointing because Eq. 23 is based on physically reasonable assumptions for the particular situation, i.e., charges of finite dimension. The HF is also based on physically reasonable assumptions, but the situation being described involves strictly one-dimensional flow.

VIII. CONCLUSIONS.

For a good streak camera record, the velocity can be obtained in any of several ways. That is, the results from the linear, quadratic, hyperbolic and spline functions all agree reasonably well. For the spline function, it is necessary to average over all, or a portion, of the results. It is possible that averaging could be avoided by stiffening the spline function, i.e., the data can be treated in larger subsets so that the spline function would take on the characteristics of a cubic function.

One of the main needs at present is a means of determining if the velocity is steady. The best means found so far are the crude instantaneous velocities, the column DXDT in the computer output, and the velocities from the spline function. However, the ripple in the

velocity makes the problem difficult. Replacement of the Telereader may make this task easier. If the present Telereader is introducing the ripple into the data, the accelerations computed from both the quadratic and the hyperbolic function may become useful.

One way of using the results of the spline function for testing the steadiness of the velocity is to examine the relation between the overall average of the velocities, and the averages over each one third of the results. This comparison suffers from the ripple also.

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Table 4

SHCT 487 05/28/68

X CON 0.014875 Y CON 0.079458 TILT 485.709084

	LINEAR	QUAD	XT FIT
A=	-0.084666	-0.140534	-0.235586
PE=	55.416235	45.461972	109.547860
B=	2.862353	2.878792	6.423913
PE=	0.126672	0.467886	113.555488
C=		-0.000749	-2.863047
PE=		79.003453	0.975894
D=			-2.210777
PE=			117.380572
OM==	0.112426	0.110686	0.116294

TIME	DISTANCE	TIME	DISTANCE	VELOCITY SPLINE	VELOCITY DXDT	VELOCITY HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	RESIDUALS QUADRATIC	RESIDUALS HYPERBOLIC
0.	0.	0.	0.	2.668442	0.	2.857525	-0.004995	-0.084666	-0.140534	-0.106563
0.872487	2.383733	59.00	30.00	2.767302	2.732111	2.847979	-0.022518	0.028967	-0.013127	-0.000281
1.877994	5.164755	127.00	65.00	2.863834	2.765792	2.619366	-1.464509	0.126059	0.098423	0.036581
3.045586	8.660897	206.00	109.00	2.920788	2.994317	2.824324	0.092771	-0.028021	-0.040771	-0.003270
4.272848	12.077581	289.00	152.00	2.885102	2.783990	2.856700	0.006155	0.068150	0.068847	0.074515
5.337000	15.255891	361.00	192.00	2.833064	2.986707	2.860286	0.001766	-0.064182	-0.053653	-0.061533
6.697281	19.069864	453.00	240.00	2.828755	2.803813	2.861706	0.000598	0.015448	0.036074	0.016424
7.850681	22.248175	531.00	280.00	2.863444	2.755601	2.862198	0.000301	0.138576	0.165590	0.139122
8.959116	25.585401	606.00	322.00	2.913261	3.0107 5	2.862454	0.000176	-0.025919	0.005356	-0.025389
9.994031	28.525339	676.00	359.00	2.924697	2.840754	2.862601	0.000114	-0.003566	0.030026	-0.002850
11.146719	31.942023	754.00	402.00	2.837072	2.963586	2.862709	0.000076	-0.120278	-0.085994	-0.119208
12.241332	34.881960	828.00	439.00	2.779026	2.686313	2.862779	0.000053	0.072382	0.105478	0.073883
13.240668	37.742440	896.00	475.00	2.858491	2.845298	2.862825	0.000040	0.089528	0.119952	0.091481
14.325524	41.000208	969.00	516.00	2.958076	3.019651	2.862863	0.000030	-0.080174	-0.054303	-0.077690
15.567320	44.575808	1053.00	561.00	2.939209	2.879379	2.862896	0.000023	-0.101317	-0.082845	-0.098177
16.616938	47.595203	1124.00	599.00	2.873077	2.876660	2.862917	0.000018	-0.116334	-0.105918	-0.112613
17.666757	50.614598	1195.00	637.00	2.827329	2.876659	2.862934	0.000015	-0.131351	-0.130642	-0.127028
18.730880	53.713451	1267.00	676.00	2.798475	2.911573	2.862948	0.000012	-0.183738	-0.194557	-0.178788
19.958483	56.971220	1350.00	717.00	2.783076	2.653764	2.862961	0.000010	0.072327	0.046102	0.078015
21.067259	60.149530	1425.00	757.00	2.752275	2.866504	2.862971	0.000008	0.067724	0.025644	0.074093
22.101672	63.089468	1499.00	794.00	2.671776	2.686313	2.862979	0.000007	0.260384	0.200847	0.267433

ACCELERATION FROM QUADRATIC = -0.001499 FOR 10 PERCENT VELOCITY CHANGE, TIME = 192.11 DISTANCE = 525.24

PERCENT CHANGE IN VELOCITY FROM QUADRATIC -1.15

RMS ERROR IN SPLINE FUNCTION = 0.086828

VEL 1ST 3RD = 2.843239 VEL 2ND 3RD = 2.875805 VEL 3RD 3RD = 2.822124 OVERALL VEL = 2.847056
PER DIF = -0.134063 PER DIF = 1.009788 PER DIF = -0.875725

Table 5

SHOT 502 05/28/68

X CON 0.009916 Y CON 0.038485 TILT 304.928566

	LINEAR	QUAD	XT FIT
A=	-0,241360	-0,126033	-0,441342
PE=	16,366205	32,720119	49,424295
B=	3,304332	3,266332	12,830691
PE=	0,103689	0,298840	55,798253
C=		0,001936	-3,291027
PE=		24,774400	0,374413
D=			-3,867505
PE=			56,834837
OME=	0,097369	0,073298	0,145669

TIME	DISTANCE	TIME	DISTANCE	SPLINE	VELOCITY DXOT	VELOCITY HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	RESIDUALS QUADRATIC	RESIDUALS HYPERBOLIC
0.	0.	0.	0.	2,910044	0.	3,288057	-0,001536	-0,241360	-0,126033	-0,114116
0,549768	1,693333	56,00	44,00	3,186107	3,080087	3,286991	-0,002433	-0,118077	-0,023056	-0,000051
1,570099	5,041515	160,00	131,00	3,282381	3,281467	3,282610	-0,007328	-0,094748	-0,034310	0,003757
2,693627	8,659091	275,00	225,00	3,185248	3,205569	3,258509	-0,055641	0,016708	0,043592	0,081527
3,768286	12,084242	384,00	314,00	3,269400	3,202092	-1,222320	-90,979646	0,126071	0,125703	-0,233134
4,454867	14,393333	454,00	374,00	3,343736	3,363183	3,162243	0,438514	0,085665	0,070140	0,240769
5,416077	17,626060	552,00	458,00	3,331152	3,363183	3,272500	0,023928	0,029097	-0,004580	0,124461
6,456241	20,974242	658,00	545,00	3,273603	3,218899	3,284398	0,005122	0,117961	0,068672	0,187958
7,545104	24,591818	769,00	639,00	3,277011	3,322344	3,287742	0,001787	0,098348	0,037206	0,148778
8,270970	27,016363	843,00	702,00	3,303593	3,340210	3,288736	0,001041	0,072305	0,005813	0,111086
9,301217	30,364545	948,00	789,00	3,350283	3,249882	3,289522	0,000554	0,128402	0,057818	0,151562
10,272092	33,674242	1047,00	875,00	3,364703	3,408984	3,289944	0,000338	0,026798	-0,043880	0,035802
11,468773	37,676666	1169,00	979,00	3,287448	3,344603	3,290258	0,000202	-0,021395	-0,087163	-0,029404
12,145941	39,831818	1238,00	1035,00	3,251901	3,182598	3,290379	0,000157	0,061040	0,000505	0,043544
13,087571	42,987575	1334,00	1117,00	3,328311	3,351376	3,290505	0,000113	0,016741	-0,033562	-0,013832
14,088195	46,297272	1436,00	1203,00	3,406688	3,307633	3,290602	0,000083	0,013438	-0,022230	-0,030920
15,019656	49,529999	1531,00	1287,00	3,334768	3,470597	3,290670	0,000064	-0,141432	-0,159991	-0,198545
15,991162	52,647272	1630,00	1368,00	3,242557	3,208702	3,290725	0,000050	-0,048527	-0,045662	-0,118885
16,962542	55,803030	1729,00	1450,00	3,261637	3,248737	3,290768	0,000040	0,005476	0,033417	-0,078077
17,992410	59,266666	1834,00	1540,00	3,322217	3,363184	3,290805	0,000032	-0,055133	0,003385	-0,152636
19,130602	62,961211	1950,00	1636,00	3,345826	3,245976	3,290837	0,000025	0,011287	0,108377	-0,101594
19,601165	64,616059	1998,00	1679,00	3,342288	3,516743	3,290848	0,000023	0,088666	0,025837	-0,207895

ACCELERATION FROM QUADRATIC = 0.003873 FOR 10 PERCENT VELOCITY CHANGE, TIME = 84,34 DISTANCE = 289,12

PERCENT CHANGE IN VELOCITY FROM QUADRATIC 2,32

RMS ERROR IN SPLINE FUNCTION = 0,048217

VEL 1ST 3RD = 3,256816 VEL 2ND 3RD = 3,306774 VEL 3RD 3RD = 3,321884 OVERALL VEL = 3,295158
PER DIF = -1,163597 PER DIF = 0,352529 PER DIF = 0,811070

Table 6

SHOT 504 05/28/68

X CON 0.007437 Y CON 0.038322 TILT 406.571419

	LINEAR	QUAD	XT FIT
A=	0.041350	0.004048	0.095684
PE=	162.701553	2301.595917	34.720499
B=	5.872111	5.896630	4.978614
PE=	0.170528	0.720572	24.266128
C=		-0.002233	-5.845716
PE=		169.737488	0.372124
D=			-0.879668
PE=			24.512439
OME=	0.175876	0.178675	0.218105

TIME	DISTANCE	TIME	DISTANCE	SPLINE	VELOCITY DXDT	HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	QUADRATIC	HYPERBOLIC
0.	0.	0.	0.	7.194048	0.	5.783303	-0.141900	0.041350	0.004048	0.108773
0.227070	1.417924	31.00	37.00	5.542879	6.244436	5.732315	-0.347537	-0.043194	-0.075043	-0.000867
0.491232	2.874170	67.00	75.00	5.322147	5.512692	5.525627	-1.648091	0.051751	0.025955	0.036776
1.224692	7.051297	167.00	184.00	6.348724	5.695100	5.440011	2.351743	0.181582	0.170959	0.411558
1.502127	9.159022	205.00	239.00	6.268325	7.597191	5.721067	0.400504	-0.297015	-0.302526	-0.136751
1.971707	11.764937	269.00	307.00	5.919747	5.549455	5.805218	0.074169	-0.145502	-0.143142	-0.030997
2.631736	15.558841	359.00	406.00	5.447474	5.748087	5.829983	0.017959	-0.063643	-0.051884	0.016781
3.248084	18.969523	443.00	495.00	5.425302	5.533699	5.837106	0.007271	0.144937	0.163714	0.201918
3.483157	20.157513	475.00	526.00	5.632433	5.053711	5.838590	0.005474	0.337320	0.358328	0.386255
4.399345	25.637598	600.00	669.00	6.239988	5.981393	5.841817	0.002215	0.237197	0.264541	0.257120
5.256129	31.079360	717.00	811.00	6.026840	6.351381	5.843194	0.001152	-0.173433	-0.143556	-0.178813
5.784266	34.068497	789.00	889.00	5.806229	5.659782	5.843708	0.000819	-0.061294	-0.031490	-0.081802
6.172884	36.329511	842.00	948.00	5.827194	5.818092	5.843992	0.000651	-0.040301	-0.011245	-0.071791
6.583248	38.820458	898.00	1013.00	5.910633	6.070089	5.844231	0.000521	-0.121544	-0.094217	-0.164522
8.305950	49.014182	1133.00	1279.00	5.808304	5.917287	5.844840	0.000236	-0.199368	-0.187082	0.289783
8.555521	50.355461	1167.00	1314.00	5.765190	5.374351	5.844896	0.000214	-0.075142	-0.066134	-0.172355
9.119995	53.689498	1244.00	1401.00	5.849564	5.906442	5.845004	0.000173	-0.094521	-0.093955	-0.207065
9.405810	55.414001	1283.00	1446.00	5.845490	6.033638	5.845051	0.000156	-0.140687	-0.144938	-0.260973
9.699250	57.061858	1323.00	1489.00	5.611053	5.615646	5.845095	0.000141	-0.065430	-0.075006	-0.193649
9.934417	58.211526	1355.00	1519.00	5.350388	4.888728	5.845126	0.000130	0.165829	0.151709	0.031260
10.132115	59.476161	1382.00	1552.00	5.163269	6.396812	5.845151	0.000122	0.062097	0.043964	-0.077804
10.550765	61.622208	1439.00	1608.00	6.091171	5.126112	5.845199	0.000107	0.374410	0.347205	0.223232
10.872258	63.959867	1483.00	1669.00	8.559433	7.271254	5.845232	0.000097	-0.075405	-0.110109	-0.235229

ACCELERATION FROM QUADRATIC = -0.004466 FOR 10 PERCENT VELOCITY CHANGE, TIME = 132.02 DISTANCE = 739.56

PERCENT CHANGE IN VELOCITY FROM QUADRATIC -0.82

RMS ERROR IN SPLINE FUNCTION = 0.118309

VEL 1ST 3RD = 5.782626 VEL 2ND 3RD = 5.998964 VEL 3RD 3RD = 5.850241 OVERALL VEL = 5.877277
PER DIF = -1.610457 PER DIF = 2.070472 PER DIF = -0.460013

Table 7

SHOT 1 05/28/68

X CON 1,000000 Y CON 1,000000 TILT 1,000000

	LINEAR	QUAD	XT FIT
A=	1,315356	1,093134	-0,279149
PE=	5,084334	5,261212	10,456267
B=	0,793290	0,922480	-2,307701
PE=	1,196761	2,540953	2,860731
C=		-0,009914	-0,749299
PE=		17,538322	0,630930
D=			0,610486
PE=			7,135210
QME=	0,198779	0,125706	0,052092

TIME	DISTANCE	TIME	DISTANCE	VELOCITY SPLINE	VELOCITY OXDT	VELOCITY HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	RESIDUALS QUADRATIC	RESIDUALS HYPERBOLIC
0,200000	0,950000	0,20	0,95	2,288553	0,	2,043905	-3,194640	0,524014	0,327233	0.000863
0,370000	1,270000	0,37	1,27	1,720853	1,882353	1,633897	-1,804407	0,338873	0,163094	-0.009832
0,600000	1,590000	0,60	1,59	1,228848	1,391304	1,329675	-0,958913	0,201330	0,053053	0.007306
0,870000	1,900000	0,87	1,90	0,980303	1,148148	1,137288	-0,524138	0,105518	-0,011813	0.027740
1,160000	2,220000	1,16	2,22	1,031214	1,103448	1,020595	-0,306465	0,015572	-0,070130	0.019124
1,470000	2,540000	1,47	2,54	1,141560	1,032258	0,945770	-0,188871	-0,058508	-0,112244	0.002977
1,790000	2,860000	1,79	2,86	1,003649	1,000000	0,896880	-0,122959	-0,124655	-0,147393	-0.022758
2,150000	3,180000	2,15	3,18	0,798018	0,888889	0,860897	-0,080854	-0,159071	-0,149363	-0.026810
2,520000	3,490000	2,52	3,49	0,781363	0,837838	0,836076	-0,055440	-0,175553	-0,135176	-0.023158
2,910000	3,810000	2,91	3,81	0,842586	0,820513	0,817914	-0,038981	-0,186170	-0,116405	-0.020837
3,660000	4,440000	3,66	4,44	0,818484	0,840000	0,795930	-0,021839	-0,221203	-0,103398	-0.046040
4,510000	5,080000	4,51	5,08	0,737124	0,752941	0,781733	-0,012669	-0,180907	-0,028140	-0.016479
5,340000	5,720000	5,34	5,72	0,757490	0,771084	0,773316	-0,008072	-0,168476	0,016463	-0.011396
6,180000	6,350000	6,18	6,35	0,788472	0,750000	0,767742	-0,005432	-0,132112	0,065406	0.005694
7,000000	6,980000	7,00	6,98	0,742453	0,768293	0,763981	-0,003859	-0,111615	0,084689	0.003613
7,850000	7,620000	7,85	7,62	0,715023	0,752941	0,761179	-0,002808	-0,077318	0,103652	0.011743
8,700000	8,260000	8,70	8,26	0,806246	0,752941	0,759109	-0,002107	-0,043022	0,108289	0.017824
9,560000	8,890000	9,56	8,89	0,852018	0,732558	0,757520	-0,001617	0,009207	0,115929	0.039944
10,140000	9,520000	10,14	9,52	0,762562	1,086207	0,756657	-0,001369	-0,160684	-0,092315	-0.150951
11,260000	10,160000	11,26	10,16	0,636505	0,571429	0,755334	-0,001017	0,087800	0,063234	0.055727
12,120000	10,800000	12,12	10,80	0,730122	0,744186	0,754546	-0,000824	0,130030	0,017219	0.064963
12,970000	11,430000	12,97	11,43	0,792435	0,741176	0,753910	-0,000679	0,174326	-0,040113	0.076048
13,820000	12,060000	13,82	12,06	0,630775	0,741176	0,753383	-0,000566	0,218623	-0,111772	0.086641

ACCELERATION FROM QUADRATIC = -0,019829 FOR 10 PERCENT VELOCITY CHANGE, TIME = 4,65 DISTANCE = 5.17

PERCENT CHANGE IN VELOCITY FROM QUADRATIC -29,71

RMS ERROR IN SPLINE FUNCTION = 0,045322

VEL 1ST 3RD = 0,948462 VEL 2ND 3RD = 0,764181 VEL 3RD 3RD = 0,733789 OVERALL VEL = 0,815477
PER DIF = 16,307612 PER DIF = -6,290385 PER DIF = -10,017229

Table 8

SHOT 2 05/28/68

X CON 1.000000 Y CON 1.000000 TILT 1.000000

	LINEAR	QUAD	XT FIT
A=	0.840735	0.625852	-0.020000
PE=	8.237436	8.392907	5.679419
B=	0.965705	1.323375	-1.467674
PE=	3.061271	4.765530	0.645615
C=		-0.079827	-0.851769
PE=		17.050574	0.287784
D=			0.200308
PE=			1.775519
OME=	0.173594	0.094346	0.028346

TIME	DISTANCE	TIME	DISTANCE	VELOCITY SPLINE	VELOCITY DXDT	VELOCITY HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	RESIDUALS QUADRATIC	RESIDUALS HYPERBOLIC
0.080000	0.510000	0.08	0.51	3.156705	0.	3.903271	-21.766315	0.407992	0.221211	-0.000471
0.160000	0.760000	0.16	0.76	2.745391	3.125000	2.698874	-10.250658	0.235248	0.075549	0.007600
0.260000	1.020000	0.26	1.02	2.156622	2.600000	1.983607	-4.916889	0.071819	-0.055467	-0.022633
0.430000	1.270000	0.43	1.27	1.353279	1.470588	1.455462	-1.915306	-0.014012	-0.089857	0.012691
0.630000	1.520000	0.63	1.52	1.094520	1.250000	1.199681	-0.837951	-0.070871	-0.092105	0.024703
0.840000	1.780000	0.84	1.78	1.155201	1.238095	1.073406	-0.426065	-0.128073	-0.098839	0.001889
1.080000	2.030000	1.08	2.03	1.084542	1.041667	0.998104	-0.228579	-0.140304	-0.068013	-0.000464
1.340000	2.290000	1.34	2.29	0.971098	1.000000	0.952874	-0.131272	-0.155220	-0.034163	-0.007379
1.590000	2.540000	1.59	2.54	0.945005	1.000000	0.926610	-0.083603	-0.163794	-0.011793	-0.022690
1.850000	2.790000	1.85	2.79	0.946139	0.961538	0.908833	-0.055661	-0.162711	0.010887	-0.034239
2.140000	3.050000	2.14	3.05	0.914288	0.896552	0.895567	-0.037428	-0.142657	0.042298	-0.032728
2.720000	3.560000	2.72	3.56	0.837917	0.879310	0.879898	-0.019264	-0.092548	0.074838	-0.028344
3.330000	4.060000	3.33	4.06	0.805622	0.819672	0.871017	-0.010904	-0.003468	0.087494	0.005429
3.960000	4.570000	3.96	4.57	0.835364	0.809524	0.865629	-0.006663	0.094926	0.044597	0.042334
4.260000	4.830000	4.26	4.83	0.876009	0.866667	0.863828	-0.005407	0.124637	-0.015244	0.041743
4.540000	5.080000	4.54	5.08	0.929348	0.892857	0.862445	-0.004504	0.145034	-0.091394	0.033415

ACCELERATION FROM QUADRATIC = -0.159655 FOR 10 PERCENT VELOCITY CHANGE, TIMP = 0.83 DISTANCE = 1.67

PERCENT CHANGE IN VELOCITY FROM QUADRATIC -54.77

RMS ERROR IN SPLINE FUNCTION = 0.015501

VEL 1ST 3RD = 1.341647 VEL 2ND 3RD = 0.887943 VEL 3RD 3RD = 0.837688 OVERALL VEL = 1.022426
PER DIF = 31.221890 PER DIF = -13.153342 PER DIF = -18.068548

Table 9

SHOT 6 05/28/68

X CON 1.000000 Y CON 1.000000 TILT 1.000000

	LINEAR	QUAD	XT FIT
A=	1.082288	0.820030	-0.034024
PE=	10.396600	11.592932	0.523229
B=	0.821405	1.008531	-1.985459
PE=	2.151598	4.202486	0.148627
C=		-0.014309	-0.771562
PE=		21.730545	0.066099
D=			0.372527
PE=			0.263441
OME=	0.346883	0.234570	0.086681

TIME	DISTANCE	TIME	DISTANCE	VELOCITY SPLINE	VELOCITY OXOT	VELOCITY HYPERBOLIC	ACCELERATION HYPERBOLIC	RESIDUALS LINEAR	RESIDUALS QUADRATIC	RESIDUALS HYPERBOL.
0.050000	0.320000	0.05	0.32	4.194702	0.	4.124179	-15.869375	0.803359	0.550421	0.000040
0.140000	0.640000	0.14	0.64	3.555459	3.555556	3.050116	-8.891453	0.557285	0.320944	-0.001769
0.260000	0.950000	0.26	0.95	2.523114	2.583333	2.267572	-4.730266	0.345854	0.131281	0.002372
0.420000	1.270000	0.42	1.27	1.377600	2.000000	1.724500	-2.404808	0.157278	-0.028911	-0.003140
0.650000	1.590000	0.65	1.59	1.020723	1.391304	1.344019	-1.119691	0.026201	-0.120471	0.024195
0.910000	1.900000	0.91	1.90	1.310557	1.192308	1.135443	-0.567444	-0.070233	-0.174056	0.033467
1.180000	2.220000	1.18	2.22	1.258856	1.185185	1.019884	-0.319893	-0.168454	-0.229827	0.002950
1.500000	2.540000	1.50	2.54	1.031130	1.000000	0.942263	-0.182322	-0.225605	-0.239369	-0.004267
2.160000	3.180000	2.16	3.18	0.855181	0.969697	0.864884	-0.073699	-0.323478	-0.248303	-0.051734
2.870000	3.810000	2.87	3.81	0.860549	0.887324	0.828490	-0.035113	-0.370280	-0.213347	-0.082174
3.630000	4.440000	3.63	4.44	0.826123	0.828947	0.808924	-0.018669	-0.370013	-0.147548	-0.090737
4.450000	5.080000	4.45	5.08	0.778751	0.780488	0.797299	-0.010673	-0.342461	-0.055357	-0.072628
5.280000	5.720000	5.28	5.72	0.755623	0.771084	0.790295	-0.006628	-0.300695	0.026168	-0.054007
6.090000	6.350000	6.09	6.35	0.748001	0.777778	0.785894	-0.004435	-0.265538	0.081299	-0.045770
7.810000	7.620000	7.81	7.62	0.750206	0.738372	0.780502	-0.002185	-0.122542	0.203879	0.030786
9.500000	8.890000	9.50	8.89	0.756500	0.751479	0.777703	-0.001244	-0.004368	0.219710	0.077249
11.170000	10.160000	11.17	10.16	0.746681	0.760479	0.776055	-0.000778	0.097378	0.140036	0.104550
12.890000	11.430000	12.89	11.43	0.745499	0.738372	0.774965	-0.000513	0.240194	0.012569	0.168342
14.560000	12.700000	14.56	12.70	0.777344	0.760479	0.774247	-0.000360	0.341939	-0.229118	0.191898

ACCELERATION FROM QUADRATIC = -0.028617 FOR 10 PERCENT VELOCITY CHANGE, TIME = 3.52 DISTANCE = 4.20

PERCENT CHANGE IN VELOCITY FROM QUADRATIC -41.31

RMS ERROR IN SPLINE FUNCTION = 0.038840

VEL 1ST 3RD = 1.058494 VEL 2ND 3RD = 0.751814 VEL 3RD 3RD = 0.751299 OVERALL VEL = 0.853869
PER DIF = 23.964420 PER DIF = -11.952039 PER DIF = -12.012380

READ END OF FILE ON SYSIN1 EXECUTION TERMINATED

TABLE 10

Coefficients for the Hyperbolic Function and Their Errors

% error is based on one standard deviation

Shot	L/d	A (mm x μsec)	B (mm)	C (mm/μsec)	D (μsec)	QME of fit mm
487*	10.0	-0.23±110%	6.4±113%	-2.9±1.0%	2.2±117%	0.12
502*	5.0	-0.44±49	12.8±56	-3.29±0.4	-3.9±57	0.15
504*	10.0	0.09±35	5.0±24	-5.85±0.4	-0.9±24	0.22
1**	2.5	-2.80±10	-23.1±3	-7.49±0.6	0.6±7	0.52
2**	1.0	-0.20±6	-14.7±0.6	-8.52±0.3	0.2±2	0.28
3**	2.5	-0.34±1	-19.8±0.1	-7.72±0.07	0.4±0.3	0.87

* Propellant charges.

** Tetryl charges. Coefficients and QME have been converted for x in mm.

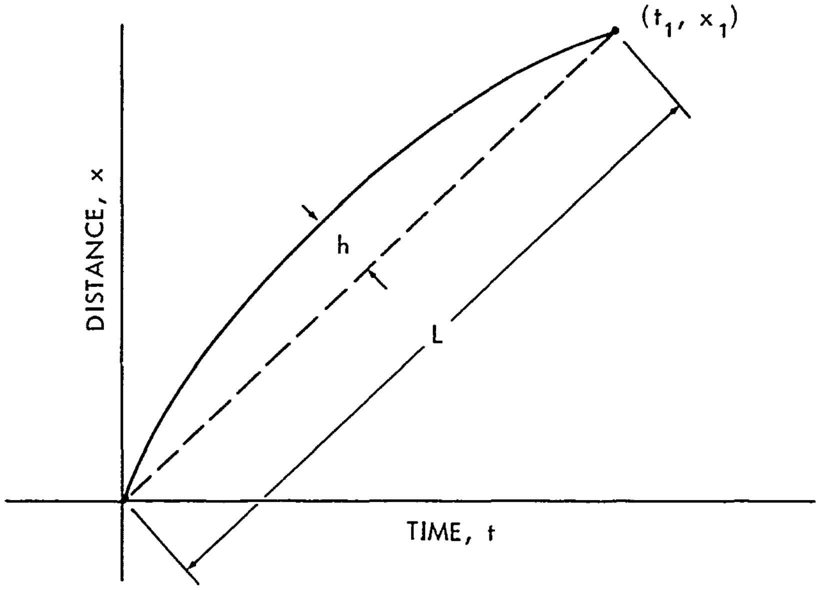

FIG. 1 HYPOTHETICAL STREAK CAMERA RECORD

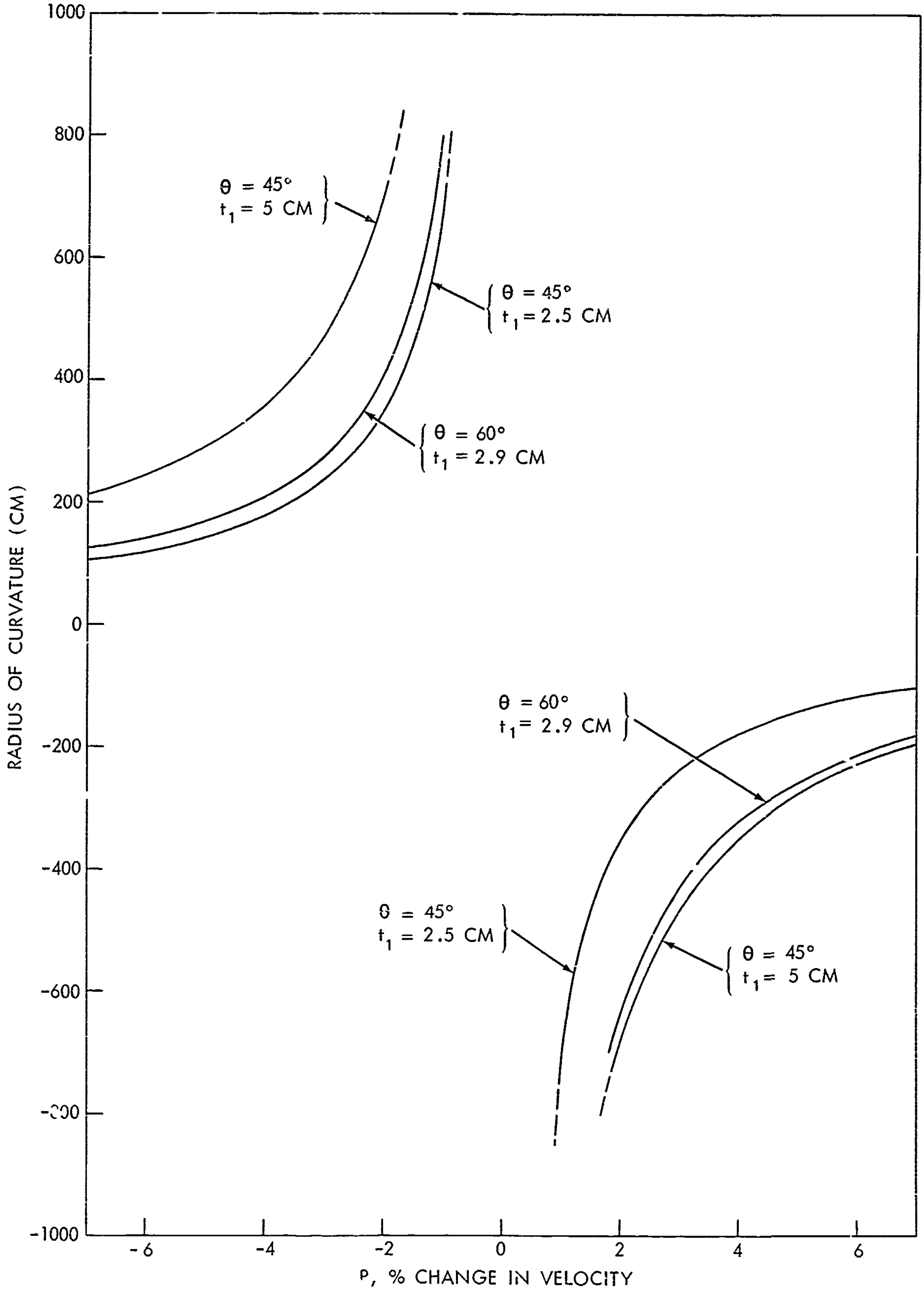

FIG. 2 RADIUS OF CURVATURE, R, VS % VELOCITY CHANGE, P

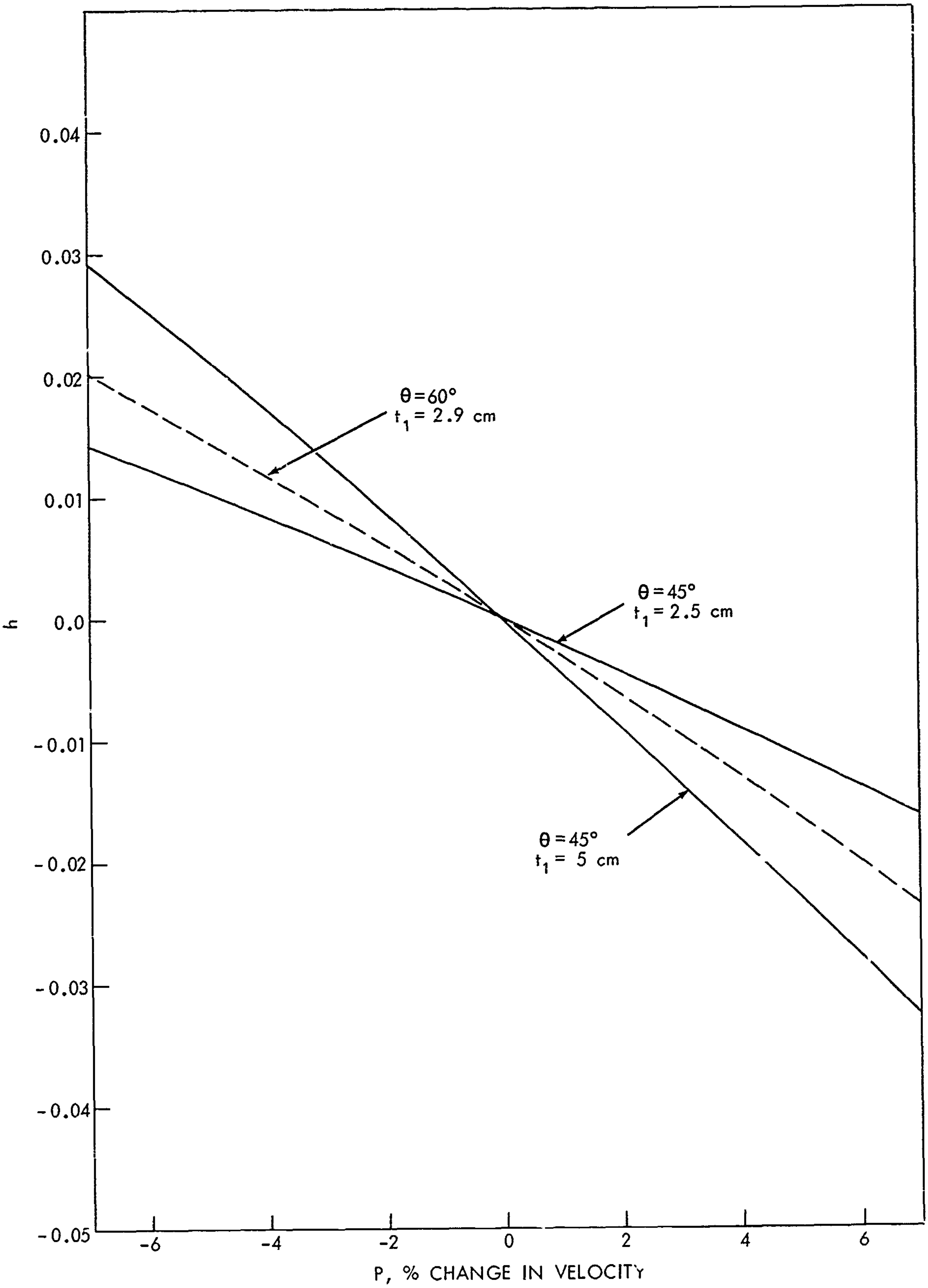

FIG. 3 h VS % CHANGE IN VELOCITY, P

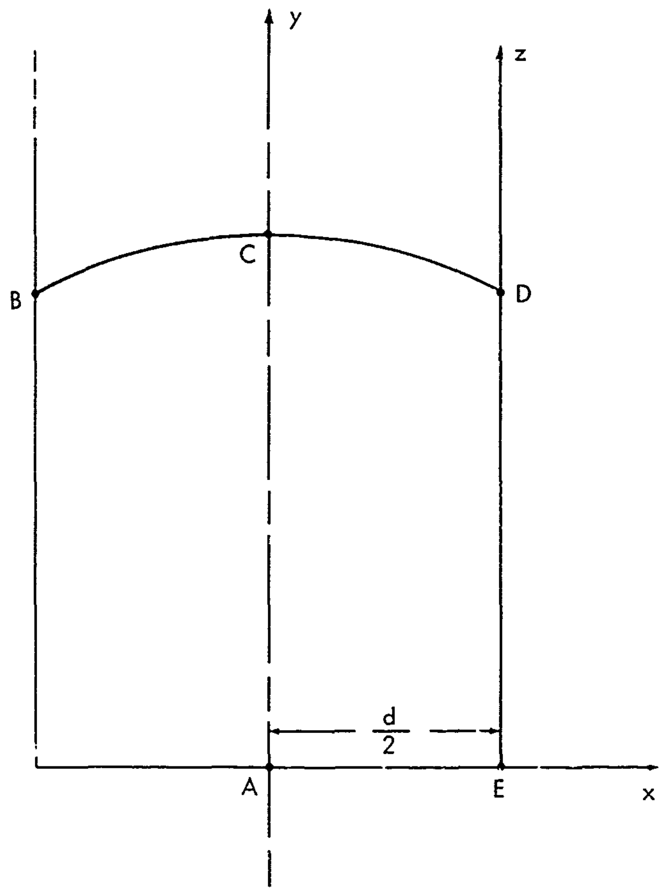

FIG. 4 SPHERICAL FRONT IN A CHARGE OF EXPLOSIVE

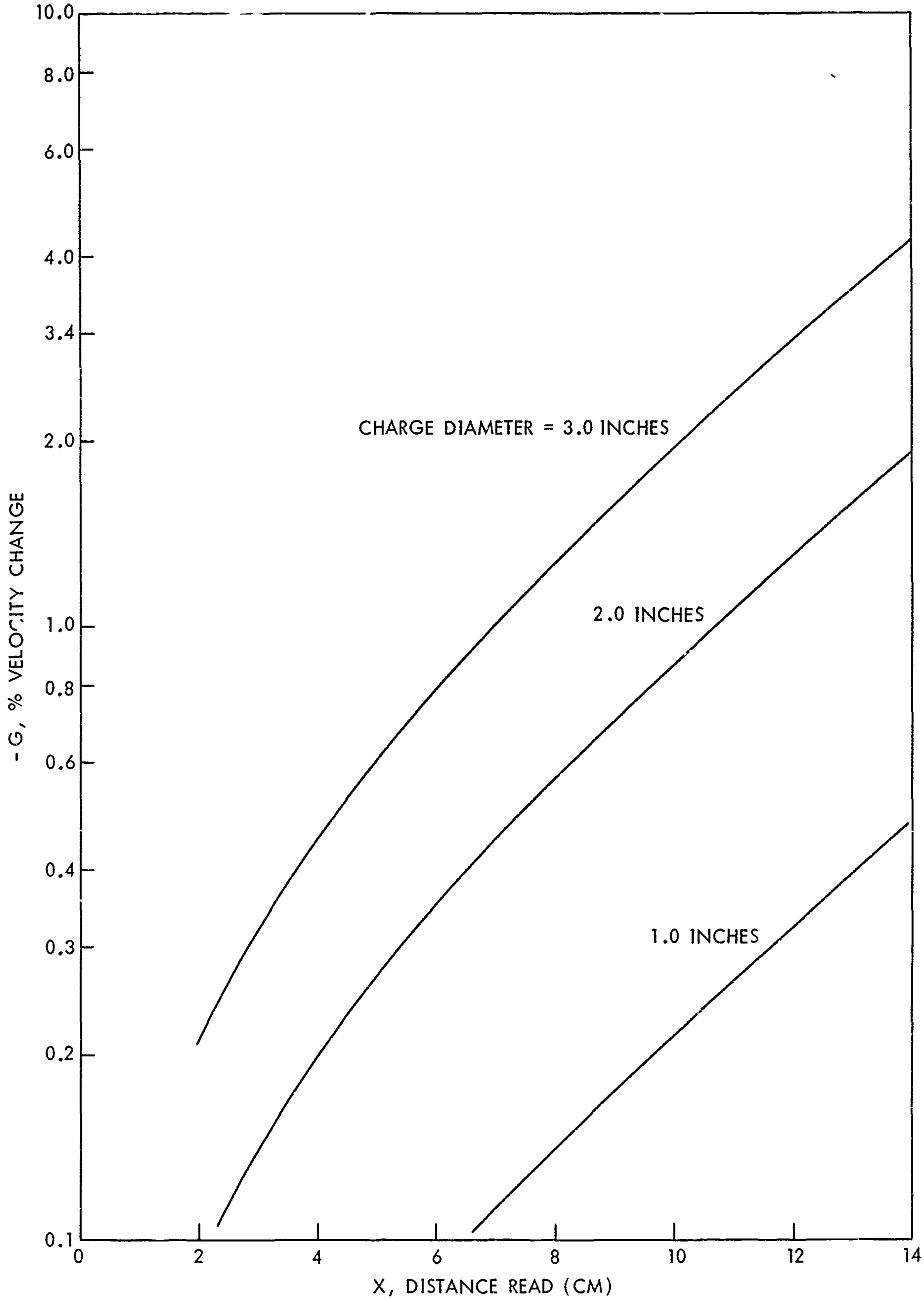

FIG. 5 -G, % CHANGE IN VELOCITY DUE TO GEOMETRY VS DISTANCE READ (FOR 10 INCH LONG CHARGES)

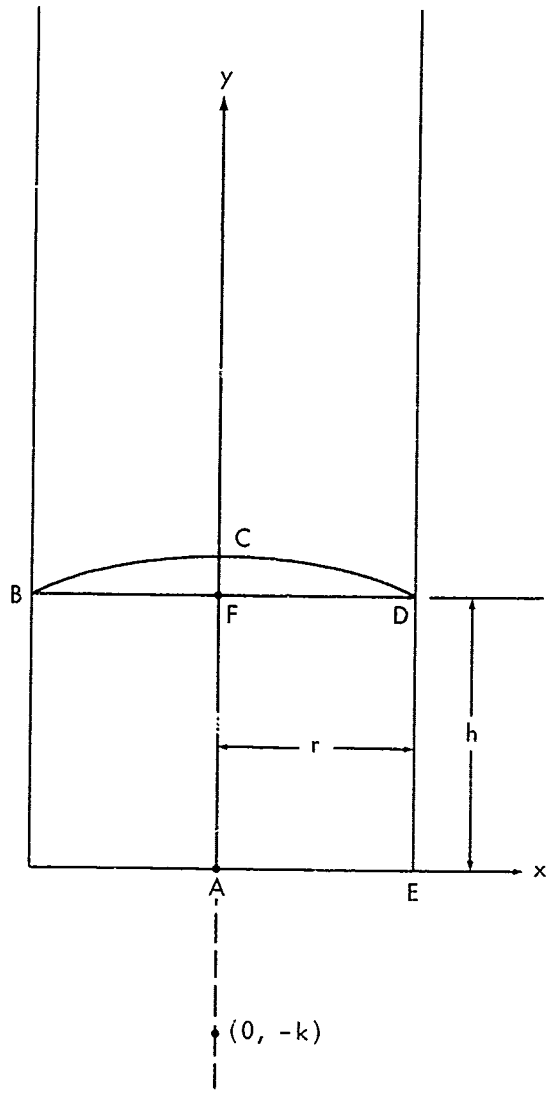

FIG. 6 GEOMETRY FOR BOOSTERED CHARGE

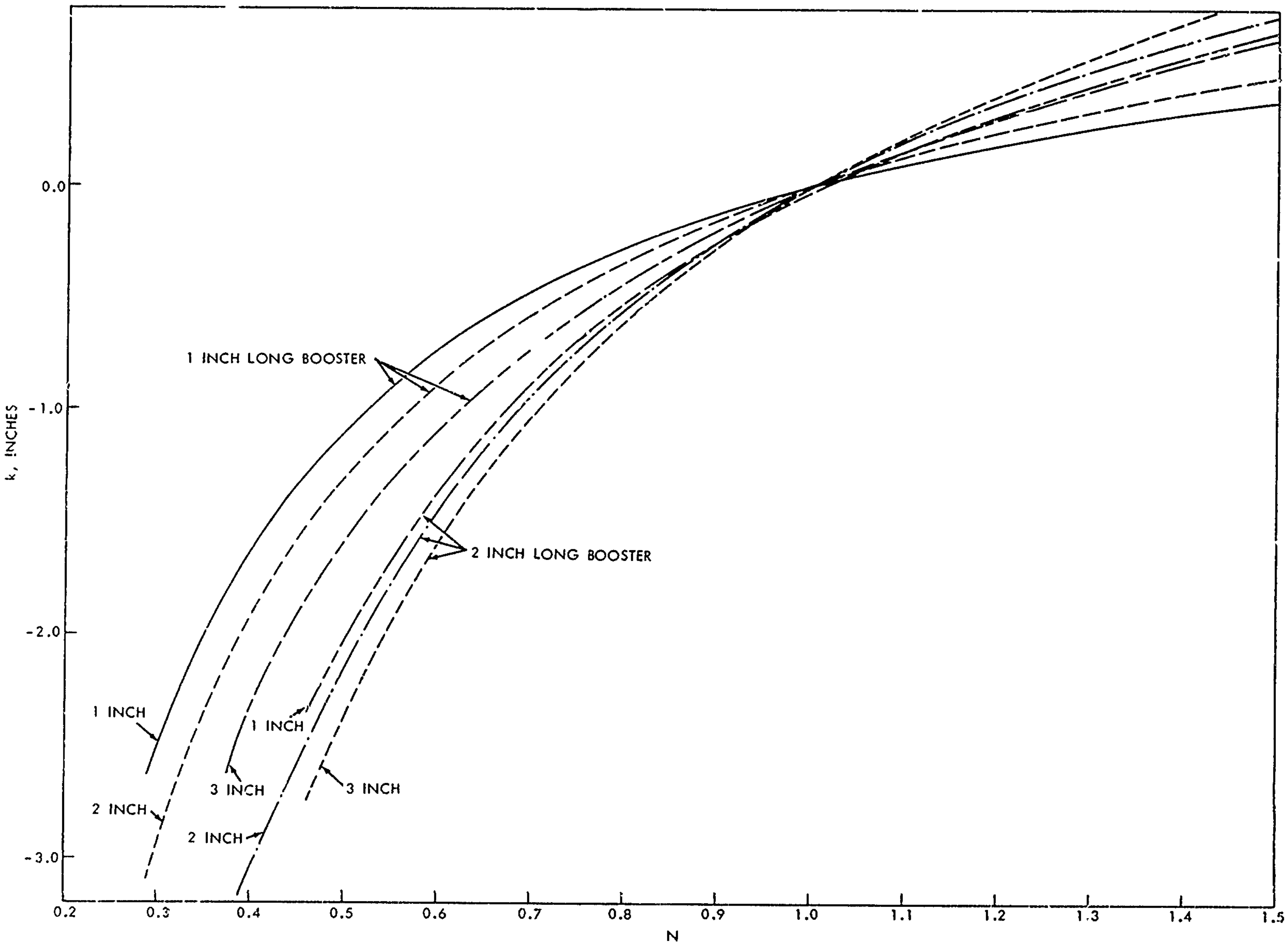

FIG. 7 k VS N FOR 1 INCH AND 2 INCH LONG TETRYL BOOSTERS

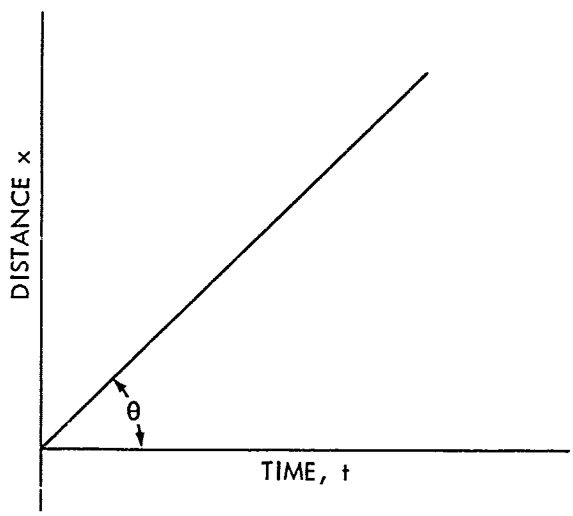

FIG. 8 HYPOTHETICAL STREAK CAMERA TRACE

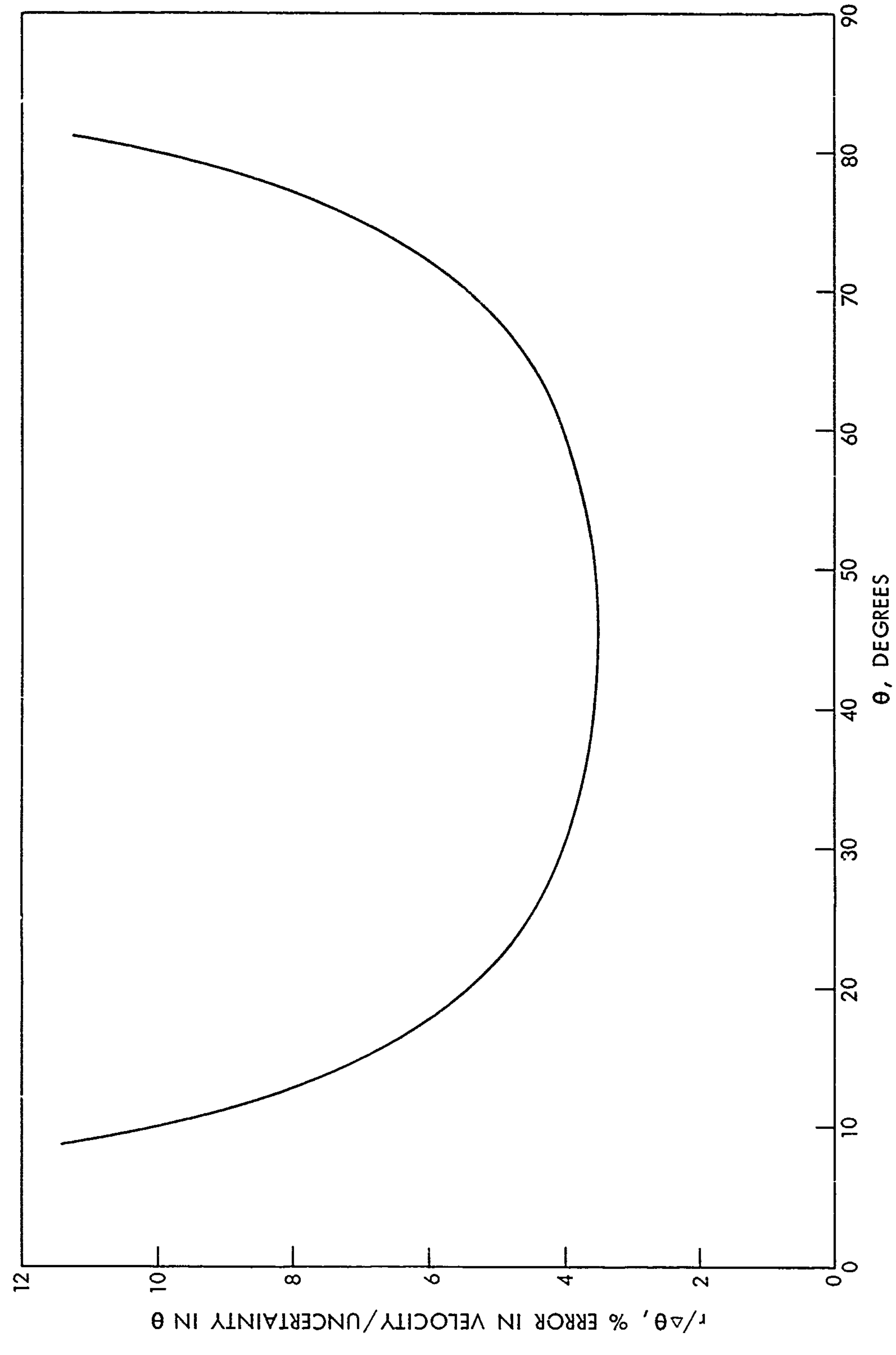

FIG. 9 ERROR IN VELOCITY WHEN DETERMINED BY MEASURING THE ANGLE θ

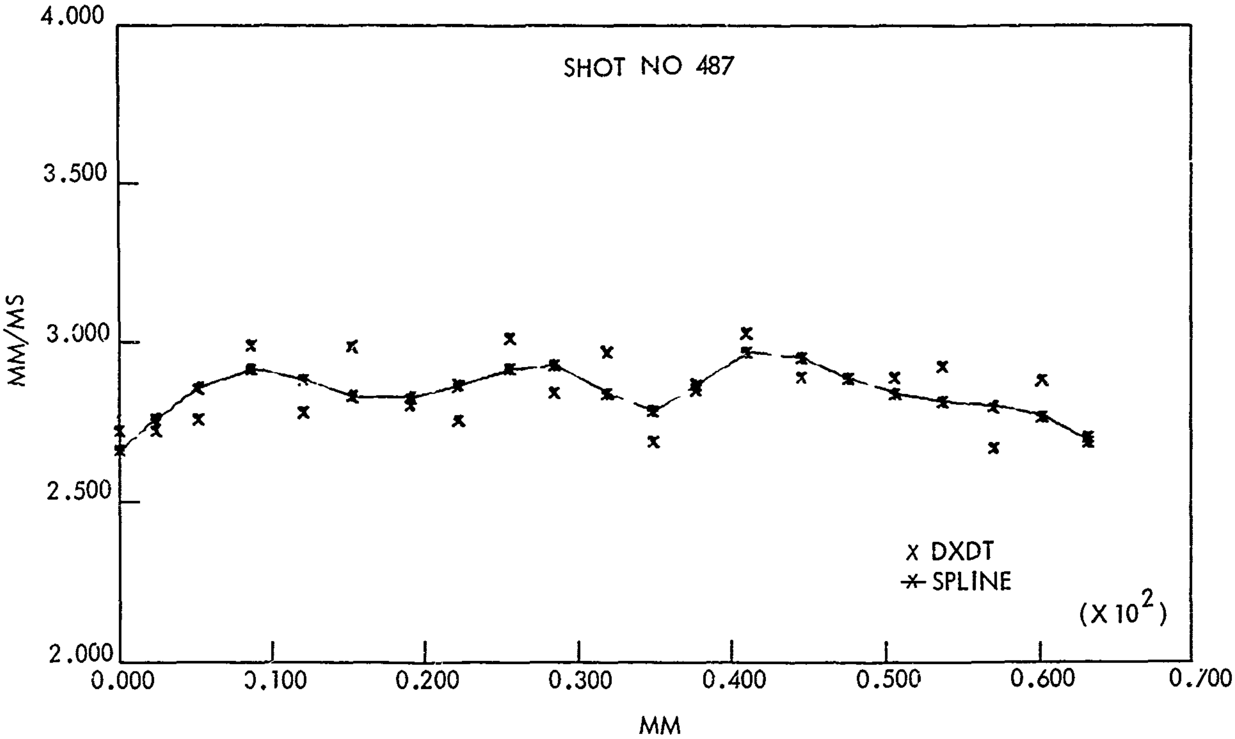

FIG. 10 VELOCITIES FROM CRUDE DIFFERENTIATION AND FROM THE SPLINE FUNCTION FOR SHOT 487

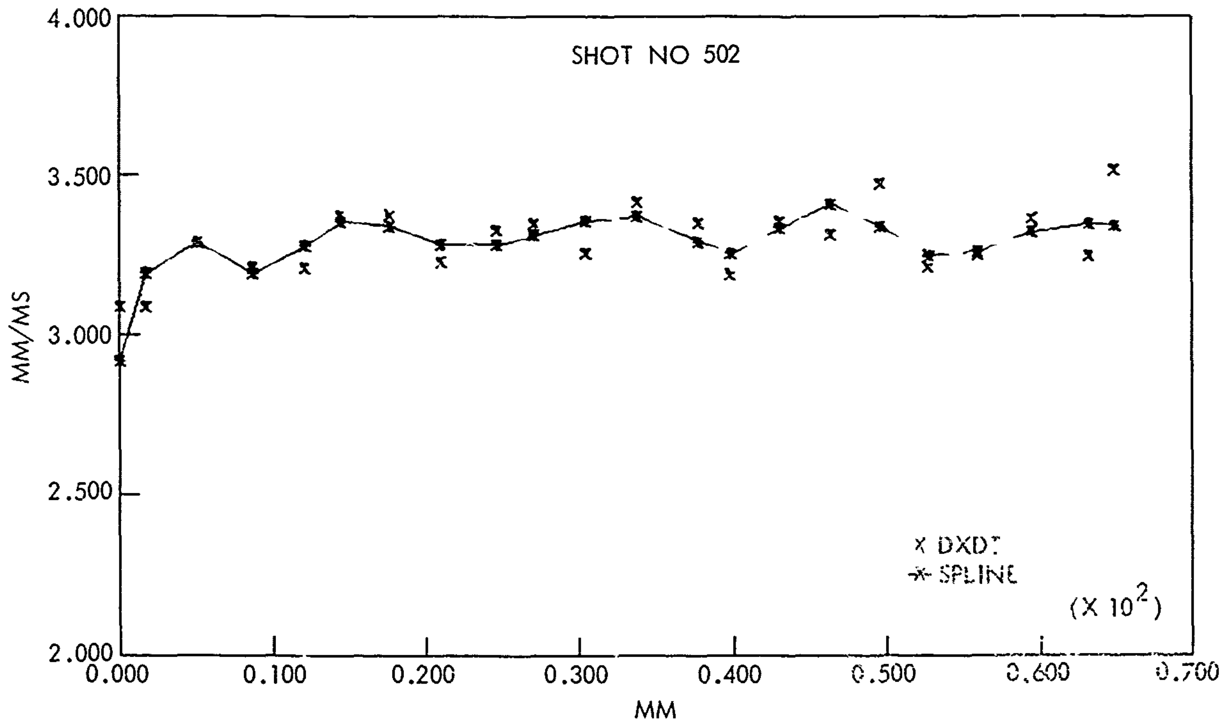

FIG. 11 VELOCITIES FROM CRUDE DIFFERENTIATION AND FROM THE SPLINE FUNCTION FOR SHOT 502

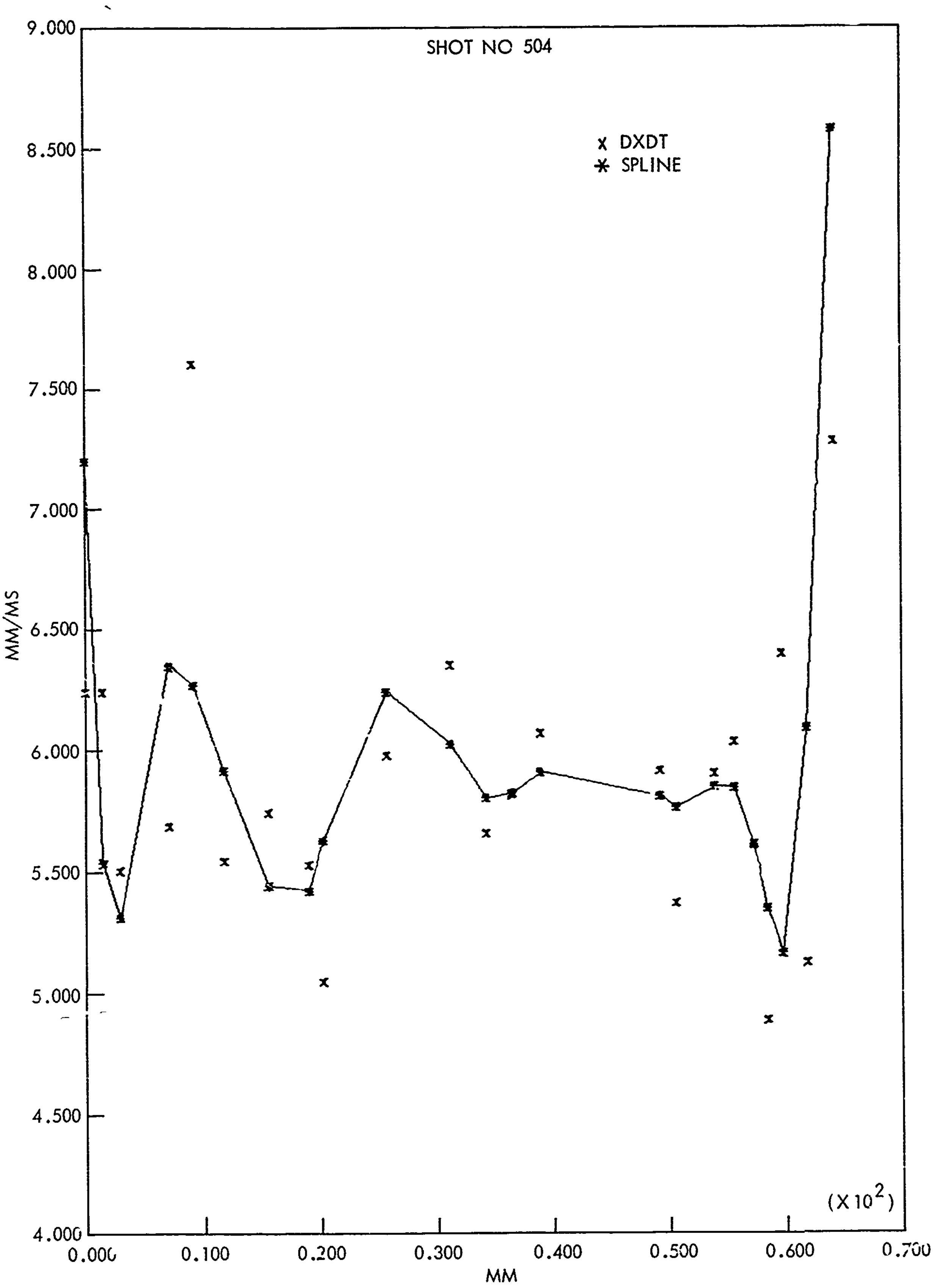

FIG. 12 VELOCITIES FROM CRUDE DIFFERENTIATION AND FROM THE SPLINE FUNCTION FOR SHOT 504

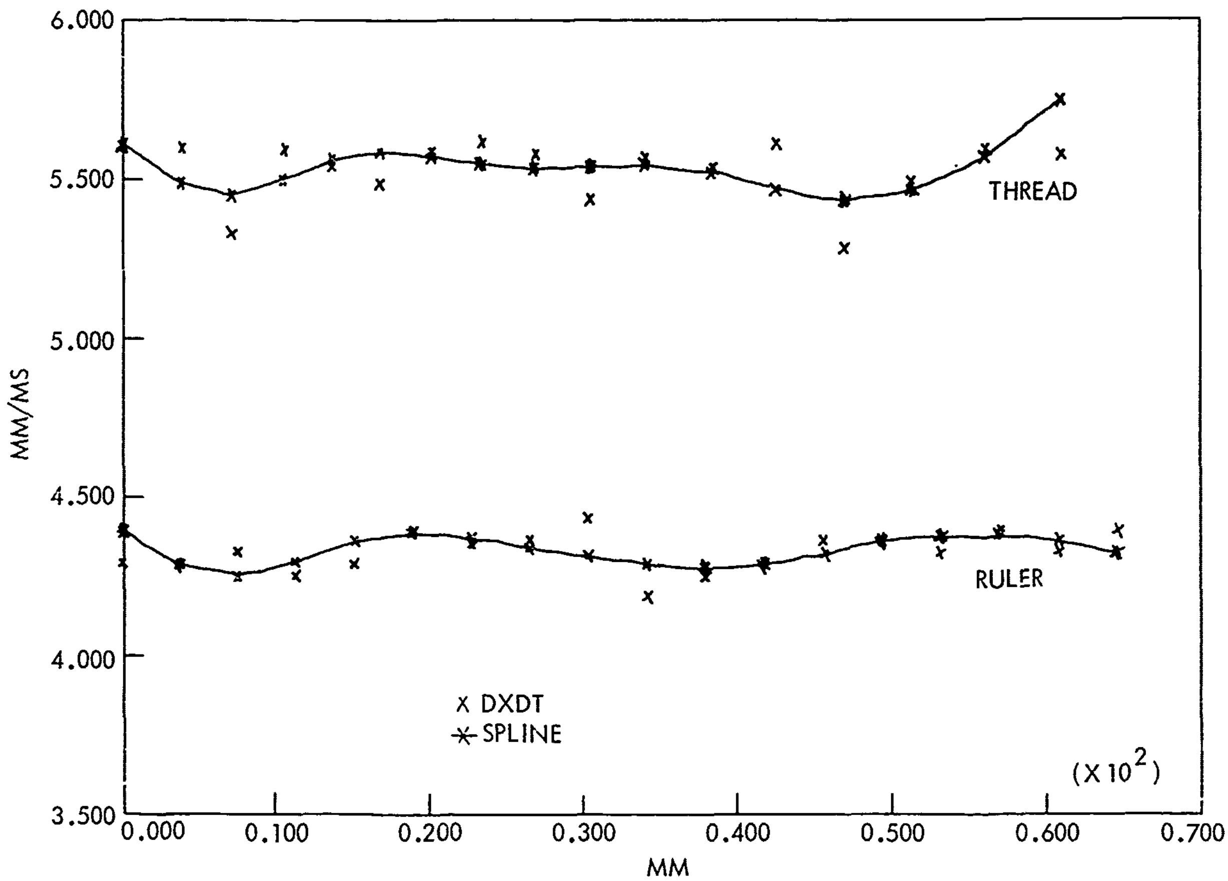

FIG. 13 VELOCITIES FROM SIMULATED RECORDS

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13. ABSTRACT

Some of the problems associated with measuring the detonation velocities of cylindrical charges are discussed. The streak camera is used as the recording instrument so that data reduction requires differentiation of numerical data. The emphasis is on methods of determining if the records represent steady or nonsteady events.

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Naval Ordnance Laboratory, White Oak, Md.
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